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Majority Ion Heating Near the Ion-ion Hybrid Layer in Tokamaks

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Abstract. Efficient direct majority ion heating in a deuterium-tritium (D-T) reactor-grade plasma via absorption of fast magnetosonic waves in the ion cyclotron range of frequencies (ICRF) is discussed. Majority ion heating results from resonance overlap between the cyclotron layers and the D-T ion-ion hybrid layer in hot, dense plasmas for fast waves launched with high parallel wavenumbers. Analytic and numerical models are used to explore the regime in ITER plasmas.

INTRODUCTION

Ion-ion hybrid layers in multiple ion species plasmas have long been recognized as playing a significant role in RF plasma heating (1). Mode coupling of the fast magnetosonic wave to ion Bernstein waves near the hybrid layer has been shown both theoretically and experimentally to result in either enhanced minority ion absorption (1,2,3) or strong electron heating via mode conversion of fast waves to ion Bernstein waves (3,4,5), depending on the plasma and wave parameters. In both of these cases, the incident wave power is transferred primarily to the electrons either through direct Landau damping or else collisionally, through drag on the hot minority ion tail distribution. Here, wave absorption in the D-T ion-ion hybrid regime in reactor grade plasmas is considered. Scenarios which feature strong single pass absorption of the fast waves by the bulk ions in high density, high temperature D-T plasmas in devices such as ITER are presented. A simple analytic model based on the hot plasma dielectric description of the plasma (7), combined with 1D full wave hot plasma numerical models (8,9), is used to illustrate the physical basis for the strong ion absorption. Bulk ion heating results from the resonance overlap between the cyclotron layers and the hybrid layer that occurs due to the high ion temperatures and the high parallel wave number, $k_{//}$, of the waves. The dependence of the heating efficiency on physical parameters is considered along with a discussion of the relevance to current tokamak experiments.

PROTO-TYPE HEATING SCENARIOS FOR ITER

In the D-T ion-ion hybrid regime in ITER plasmas with B_{T0} = 6T, on-axis power deposition is predicted with wave frequencies of about 45 MHz, while off-axis absorption is found with lower frequencies of about 35 MHz. The $k_{//}$ launched by the antenna was chosen to be 15 m^{-1} for these examples. Parameters typical of ITER plasmas were assumed (10), with R_0=7.75 m, a=2.85 m, 50/50 D-T ion composition, $T_e(r)=T_i(r)=(19.0-0.05)*(1-r^2/a^2) + 0.05$ (keV), and $n_e(r)=(1.4-0.8)*(1-r^2/a^2)^{0.26} + 0.8$ (10^{14} cm^{-3}). Total single pass absorption as calculated with the CARDS (8) code is essentially complete, with absorption by the majority D ions amounting to 53% in the on-axis scenario and 87% in the off-axis scenario. Power deposition profiles obtained with the FELICE code (9) are broad but peak strongly near the ion-ion hybrid layer, as illustrated in Figure 1. Global power splits obtained with the FELICE code indicate that deuterium absorption amounts to 64% in the on-axis scenario and 90% in the off-axis scenario, in good agreement with the CARDS analysis.

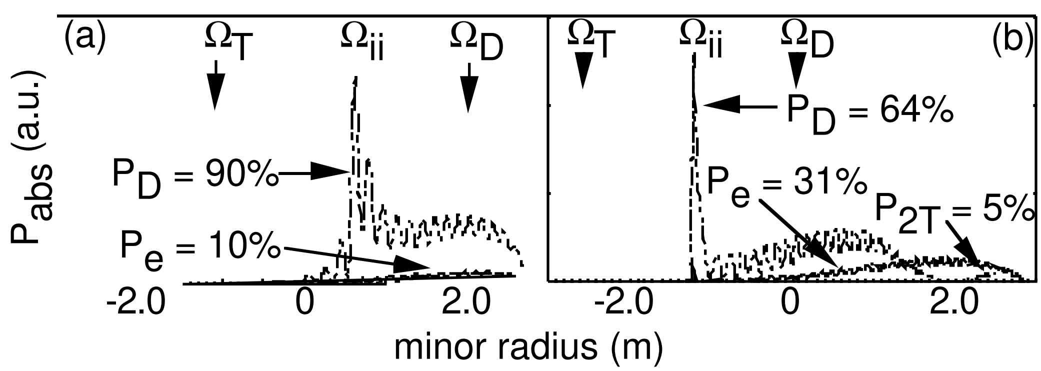

FIGURE 1. Power deposition profiles for off-axis (a) and on-axis (b) heating scenarios.

ANALYTIC MODEL

Strong fundamental majority ion heating in the D-T ion-ion hybrid regime can be understood using local hot plasma theory (7). A simple expression for the local power absorption by ions can be derived by assuming that $E_{//} \ll E_{\perp}$, and by expanding the dielectric tensor elements, retaining finite temperature effects but neglecting finite Larmor radius (FLR) corrections, and utilizing the large argument expansion of the plasma dispersion function. Under these assumptions, the ion absorption in the D-T ion-ion hybrid regime is given by:

$$P_{abs,i} = \frac{|E_+^2|}{16\sqrt{\pi}} \omega_{pe}^2 \frac{m_e}{m_p} \left[\frac{\eta_D}{2\ k_{//} v_D} e^{-\varsigma_{-1D}^2} + \frac{\eta_T}{3\ k_{//} v_T} e^{-\varsigma_{-1T}^2} \right] \tag{1}$$

where $\eta_j = n_j/n_e$ and $\zeta_{-1j} = (\omega - \omega_{cj})/k_{//} v_j$. Ion power absorption is thus maximized by: (i) enhanced E_+ near the ion-ion hybrid layer; (ii) high $k_{//}$ and high T_i to broaden the resonant interaction between the ions and the waves (i.e., minimize ς_{-1}^2); and (iii) high density to increase the number of interacting ions.

Electron absorption of the waves in this low frequency, hot plasma regime is due entirely to Landau damping (2). Using Equation (1) and the expressions for P_e in reference 2, the ratio of electron to ion damping may be written as:

$$\frac{P_e}{P_i} = 4\left(\frac{\omega}{k_{//} v_e}\right)^2 \frac{m_p}{m_e}\left[\frac{\dfrac{e^{-\varsigma_e^2}}{k_{//} v_e}}{\dfrac{\eta_D}{2\ k_{//} v_D} e^{-\varsigma_{-1D}^2} + \dfrac{\eta_T}{3\ k_{//} v_T} e^{-\varsigma_{-1T}^2}}\right]\frac{\left|E_{//}^2\right|}{\left|E_+^2\right|} \tag{2}$$

where $\varsigma_e^2 = (\omega/k_{//} v_e)^2$. Near the hybrid layer in ITER, $E_{//}/E_\perp \sim 10^{-3}$, the term in brackets in Eq. (2) is approximately 2.6 e3, and $\omega/k_{//} v_e \sim 0.21\ (18 / k_{//})$, so:

$$\frac{P_e}{P_i} = 0.02\left(\frac{18}{k_{//}}\right)^2 \quad . \tag{3}$$

Hence, direct electron Landau damping increases relative to ion absorption at lower $k_{//}$'s in this regime. Mode conversion to ion Bernstein waves is negligible here, primarily because of the single pass ion absorption and minimal transmission of the fast wave through the hybrid layer to the mode conversion surface. In the limit $k_{//} \Rightarrow 0$, the tunneling parameter, η, is given by (1):

$$\eta \approx 8.45\left(\frac{R_0(m)}{7.75}\right)\left(\frac{n_e(cm^{-3})}{1.4e14}\right)^{1/2}\left(\frac{\eta_T}{0.5}\right)^{1/2} \quad . \tag{4}$$

Transmission, T, and mode conversion, C, can be estimated with $T = e^{-\eta}$ and $C = T^2(1-T^2)$. For ITER, T ~ 2e-4 and C ~ 4e-8. In contrast, for TFTR experiments in which R_0 = 2.62 m and n_e = 5e13 cm^{-3}, transmission and mode conversion can be substantial (5), particularly at finite values of $k_{//}$.

DISCUSSION

Efficient fundamental bulk ion heating in a high density, high temperature ITER plasma is predicted for fast waves launched in the ion-ion hybrid frequency range. Wave absorption is broadly localized between the two cyclotron layers, with peak absorption occurring near the hybrid layer. The dependence of the wave absorption on $k_{//}$ and temperature is displayed in Figure 2. Global power splits from FELICE are given in (a) and (c), with single pass absorption coefficients from

CARDS given in (b) and (d). Strong single pass deuterium ion heating results from high density operation, $n_{e0} \geq 8e13$ cm^{-3}, high temperature operation, $T_{i0} \geq$ 8-10 keV, and for wavenumbers $\geq$ 8-10 m^{-1}. Absorption of the waves by alpha particles remains to be addressed, since related work (11) has found it may be significant in some regimes. Electron heating via direct Landau damping or mode conversion becomes more dominant in the lower density, smaller plasmas which are found in TFTR, JET and JT-60. However, the relevance of this heating scheme to a recently developed high density, high temperature reversed shear operating regime in TFTR (12) and to TPX and CMOD plasmas remains to be evaluated.

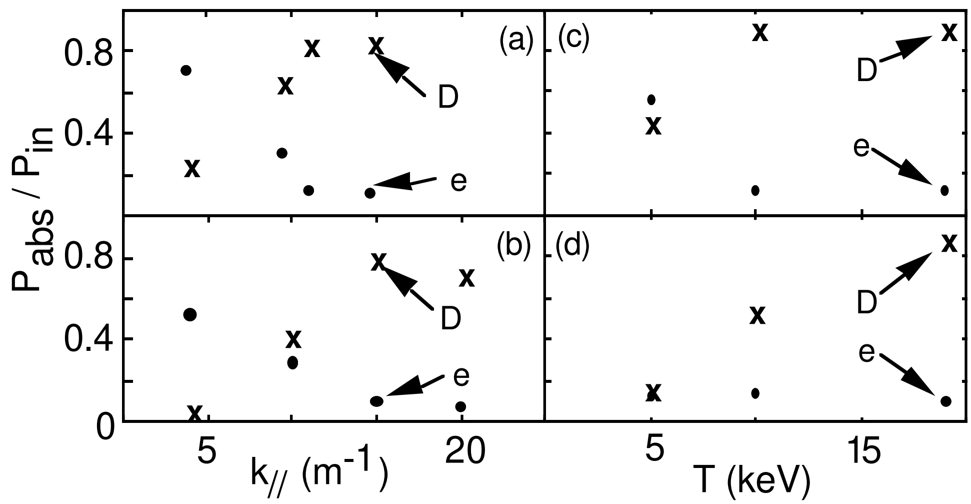

FIGURE 2. Parametric dependence of power split is given as a function of $k_{//}$ and plasma temperature.

Finally, mode conversion near the D-T ion-ion hybrid layer is suppressed by the strong single pass absorption as well as by the high density and large major radius in ITER type devices. Hence, alpha channeling via mode converted ion Bernstein waves (13) is unlikely to be viable in an ignited ITER plasma.

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